LIMITER OPTICS

RELATED APPLICATIONS

This is a continuation-in-part of Serial No. 60/178,531, filed January 25, 2000.

BACKGROUND OF THE INVENTION

1.   Field of the invention.

The invention relates in general to the control of high-powered lasers, and, in particular, to improving the reliability, safety and power output of free electron lasers.

2.   Description of the prior art.

Manmade space satellites are limited by their power requirements. Solar panels have long been used to provide power for satellites. Solar panels are limited for two reasons. First the energy received from the sun is relatively diffuse and is not adjustable. For a fixed surface area the power that can be created by the solar panel is limited. The greater the power, the larger the surface area required. Mirrors have been used in space to reflect more sunlight on a fixed area. This leads to the second limitation, the mass and volume of the solar panel needed to generate the required power level. For high power levels the mass and volume can force reductions in the remaining portions of the satellite. Even the use of mirrors reduces the mass

and volume available for launch payloads. The power limitations force most satellites to be designed to operate on the power requirements of a small household appliance.

Electrical power has always been a limiting factor for satellites, and it restricts the services that they can perform. The need for additional transponders to satisfy the demand for satellite-supplied television, e-mail, worldwide web, long distance telephones, rapid computer data transfer, and many other types of telecommunication is increasing. The number of transponders has risen from about 24 active transponders per satellite in the late 1980's to 94 active transponders on the Hughes satellite launched in late 1997. The demand for additional power over the last few years fits an exponential curve and the end is not in sight. Instead it is increasing even faster. In response to the need for additional frequencies to carry the load the Federal Communications Commission has opened up the Ka band for satellite use. Recently completed National Aeronautics and Space Administration (NASA) studies indicate that the Ka band will on occasion require the availability of up to ten times the power requirements of the lower frequency L, C and Ku bands to counter rain fade.

The additional power needed for the Ka band is required to keep the television signals broadcast to earth at an acceptable level of quality. The Ka frequency band is 26.5 to 40 gigahertz (wavelength range of 11 millimeters to 7 millimeters). The size of raindrops is typically 1 to 3 millimeters with a maximum of 5 to 7 millimeters. Although the Ka band is in a water absorption region, much of the

extinction of the signal is caused by the resonance in scattered energy resulting from the proximity of the wavelength to the raindrop size. The only practical source for the additional power required is additional electricity from the solar panels carried on the satellite.

At present the size of satellite solar panels is awkwardly large. Additional satellites in the same "space slot" can be deployed to increase the total solar panel area, and this is the direction that many satellite companies are going. A major drawback of this approach is that the output signals of the various satellites are not in phase, so interference between satellite transmissions can be a problem. The biggest drawback, however, is that the multiple satellite approach is very expensive.

One way to repower the satellites is laser power beaming, LPB. Laser beams can increase the power level an order of magnitude above that available from the sun. Further, since a laser can be tuned to a narrow frequency range, the efficiency of the solar panels can be maximized by using their optimum generating wavelength. Beaming from the earth's surface requires the laser beam to travel through our planet's atmosphere. For LPB to be effective the atmospheric path must be free of clouds. In addition, the atmosphere can cause various other problems associated with turbulence, scatter, and absorption. Sites with clear, smog-free air minimize the last two problem areas. Turbulence is handled by the use of adaptive optics.

Free electron lasers, FELs, are capable of high power without significant wavefront distortion since the light is generated in a vacuum. An ignition feedback regenerative free electron laser (FEL)

amplifier (IFRA FEL) designed by Kim, Zholents and Zolotrev does not

need cavity mirrors, a power-limiting feature of most types of lasers.

It provides greater output power than prior FELs. By feeding a portion

of the output power back through the undulator and a portion to the

photocathode emitting electrons, optical power grows without the

necessity of cavities. Their invention is disclosed in U. S. Patent

Application Ser. No. 09/361,675. Other prior art patents for free

electron lasers include Sheffield U.S. Patent No. 5,960,013 and

Edighoffer U.S. Patent No. 5,029,172. One problem with IFRA FEL is

that the portion of the beam fed back can grow in power, increasing the

output of the laser and going into a runaway situation. A further

problem with IFRA FEL is that the generated optical pulse is of the

same duration as the electron bunch that emitted the pulse. This

causes phasing problems unless the optical feedback loop can be

accurately controlled. Any portion of an electron bunch out of phase

with the optical pulse is wasted. This invention provides a means for

phasing of the feedback loop and a means for control of the internal

efficiency within the undulator so positive feedback producing a

runaway condition does not occur. This invention provides a method and

mechanism to lengthen the duration of the optical pulse fed back to the

IFRA FEL.

SUMMARY OF THE INVENTION

Limiter optics for an ignition feedback regenerative free electron

laser (FEL) amplifier, IFRA FEL, are made by using a very small pickoff

mirror to direct a portion of the IFRA FEL's output beam to a pulse expander mirror. Light reflected from the expander mirror is then passed through focusing optics, which refocuses this pulse expanded light beam to a predetermined location within the undulator of the IFRA FEL. Since it lengthens the duration of the IFRA FEL laser pulse, the next electron bunch is assured of being completely illuminated by the returned optical pulse.

The focusing optics has two Cassegrainian mirror systems. The first Cassegrainian mirror focuses the parallel light beam incident on a convex pickoff mirror to a focal point. The second Cassegrainian mirror then refocuses the light beam into a nearly parallel beam to a focal point in a predetermined location in the undulator. Mounted near the focal point between the two Cassegrainian mirrors is a movable limiter plate which controls the cutoff intensity of the pickoff beam.

In order to meet the phasing conditions, the optical pulse-length exiting the undulator must be expanded. In this way the optical pulse is not required to exactly match the electron bunch length time-wise. The feedback loop average power is planned in the IFRA FEL to be 4 kilowatt. A cooled mirror can handle over 2 kilowatts per square millimeter of surface area.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a state of the art IFRA FEL;

FIG. 2 is a drawing of one embodiment of the present invention;

FIGS. 3A, 3B, 3C are views of optically equivalent pulse expander mirrors;

FIG. 4 is an alternate embodiment of the present invention;

FIG. 5 is a comparison of light reflected from a phased step mirror and from a phased half-silvered mirror; and

FIG. 6 shows light reflected from a phased mesa mirror for Fig. 3C.

FIG. 7 shows a perspective view of the phased mesa mirror that creates the reflected light pattern of FIG. 6.

DESCRIPTION OF PREFERRED EMBODIMENT

Fig. 1 is an example of a typical ignition feedback regenerative free electron laser (FEL) amplifier, IFRA FEL, suitable for laser power beaming, LPB. An optical pulse laser 10 has an up-converter 12 take an initial ignition pulse and convert it to a suitable wavelength before it is used to illuminate photocathode 14. Up-converter 12 will not change quality or intensity of light passing through it, but does convert to the best frequency for emission of photons with a given quality and intensity. Photocathode 14 in turn emits a bunch of electrons 15 with a pulse width determined by the design parameters of laser 10 and photocathode 14. This electron bunch is immediately accelerated by an initial accelerator 16. The electron bunch is now directed through a linear accelerator 18, which may have a large number of cooled RF cavities 20 operating near room temperature. Electron bunch 15 is now accelerated by the RF cavities to a speed very close to

the speed of light. Electron bunch 15 now enters a bunch compressor 21, which reduces the electron bunch length from about 5 millimeters to about 1 millimeter with a corresponding increase in bunch height. The electron bunch is directed by steering magnets, which may be part of bunch compressor 21, to an undulator 22. Undulator 22 may contain both a linear undulator and a tapered undulator also known as a tapered wiggler. The electron bunch loses about 2 percent of its energy by emitting light, which exits undulator 22 as optical pulse 24. Electron bunch 15 is directed back into linear accelerator 18 out of phase with RF cavities 20. The bunch decelerates, giving up its energy to the RF cavities 20. Electron bunch 15 is then directed to a beam dump system 26, which is comprised of a further decelerator 28 to avoid radiation hazards and a beam dump 30.

Two pickoff mirrors 32 and 34 are placed in the path of optical pulse 24. Pickoff mirror 32 feeds a portion of optical pulse 24, approximately 5 percent, back through up-converter 12 onto photocathode 14 to generate a new electron bunch. As the energy level of optical pulse 24 increases, the feedback to photocathode 14 increases and in turn this increases the energy level of the electron bunch emitted by the photocathode to a level higher than the initial electron bunch 15. The speed at which the system operates means the output of undulator 22 may be described as a pulsed optical beam. Sample functioning levels can have pulse lengths of approximately 24 picoseconds separated by 8.4 nanoseconds.

Pickoff mirror 34 feeds a second portion, approximately 2 percent, of each optical pulse 24 via mirrors 36 back into undulator 22. If

this feedback is timed to coincide with a new electron bunch,

illumination by the optical pulse induces in-phase stimulated emission

from the electron bunch, increasing the amount of light emitted from

the electron bunch in undulator 22. As this cycle repeats, pickoff

mirror 34 continually sends back greater optical power, which in turn

increases the optical power output from undulator 22. That is more

than 2 percent of the energy is given up by the electron bunch because

of the presence of the feedback light. If the feedback is unchecked,

far more than 2 percent of the energy in the electron bunch will be

emitted. Levels that will destroy the system can be reached very

quickly, thus the concern over a runaway effect. The IFRA FEL has

output increased by the effects of both pickoff beams.

The problems with the prior art of Fig. 1 are (1) to phase the

reentrant optical pulse 24 to the new electron bunch entering undulator

22 and (2) to prevent a runaway situation. To avoid problem (2), a

mode filter, also known as a limiter plate 38, has been placed in the

feedback loop from pickoff mirror 34 to function as an automatic

cutoff.

The bunch width of the electron bunches is of the order of 24

picoseconds. The optical pulses are also of this same 24 picoseconds

width. To solve problem (1) matching the electron bunch and the

optical pulse so they pass through undulator 22 together is critical.

To complicate matters the feedback loop can develop divergence

problems, especially after passing through a limiter plate.

Fig. 2 is one embodiment of the present invention. Light excited

in undulator 22 is parallel, very coherent, and thus can be thought of

as originating from a point source. About 2 percent of it is picked off
by a pickoff means such as small (possibly as small as 2 millimeters on
a side) convex mirror 42. Convex mirror 42 may be cooled by any known
cooling techniques for mirrors. These techniques are well known and
not shown. The portion picked off, beam 40 expands and strikes a
pulse-expander-folding mirror 44. Expander mirror 44 is mounted at the
entrance pupil of two focusing optics 48 and 54. Expander mirror 44 is
designed to expand the pulse width by a desired factor, two is
practical, so that when the returned pulse arrives nearly in phase with
the incoming pulse from accelerator 18 the return pulse is twice as
wide as the incoming pulse. As a result, even if there is a small
phasing error, each point on the incoming pulse is covered by part of
the returned pulse and stimulated emission will occur in phase with the
emitted light beam. In this way the need for an optical cavity such as
that used in most lasers is eliminated. Very high power operation of
the laser is then possible since there are no cavity mirrors to damage.

Limiter assembly 46 has expander mirror 44, focusing optics 48,
limiter plate 50, adjusting means 52, and refocusing optics 54. The
effect of limiter assembly 46 is to tune pickoff beam 40 so it has
spatial and temporal uniformity of a preselected pulse duration.

Focusing optics 48 may be a pair of mirrors such as the
Cassegrainian arrangement with a central aperture 56 to allow pickoff
beam 40 to first be diverged and then refocused to a preselected
location, focal point 58. Placed near this location is limiter plate
50 which is mounted on adjusting means 52. Limiter plate 50 is a plate
of lead phthalocyanine or one of the azulenic compounds or other

similar material which becomes increasingly opaque when the energy density of light passing through exceeds design parameters. Adjusting means 52 may be a vernier drive or other similar means which moves limiter plate 50 either closer to or farther away from focal point 58 of refocused pickoff beam 40. As limiter plate 50 is moved farther from preselected focal point 58, the energy density decreases. As it moves closer, the energy density increases. Thus moving limiter plate 50 functions as an on-off control to prevent a runaway problem.

Further information can be found regarding lead phthalocyanine in "Ultrafast Transient White Light Absorption Spectroscopy of Novel Materials for Optical Limiting", S. M. Kirkpatrick et al. pp 123-127 and further information regarding Azulenic compounds "Optical Power Limiting in Some Azulenic Compounds" B. R. Kimball et al., pp 32-38. Both are in the publication Power Limiting Materials and Devices, SPIE Proc v. 3798 July 1999. Other better materials may be used in place of lead phthalocyanine as they become available.

Light that does pass through limiter plate 50 is then refocused again. This time the imaging plane of focal point 58 is refocused to point 60 within undulator 22 of IFRA FEL. The location of point 60 is chosen to maximize the efficiency of stimulated emission. The object is to provide high efficiency for further light emission. By a fundamental theorem in optics every point in a parallel beam from a point source is superimposed on the image of the point source, so temporal mixing of the two different phases of light developed by mirror 42 at focal point 58 is complete and the pulse length of the image formed in the undulator is greater in length than the pulse

length beam 24. A plurality of mirrors 70 are placed as desired to direct the refocused beam, exit beam 69, into undulator 22. Mirrors 70 then redirect exit beam 69 to an optimum point 60 in undulator 22. The exact location of point 60 is a matter of design. Ideally, point 60 is near the entrance to undulator 22. Mirrors 70 may be mounted on an optical table, not shown, which may be moved by an adjustment means, also not shown. Commercially available adjustment means include the Inchworm by Burleigh Instruments Inc., or the Nanomover Micropositioner by Melles Griot. Mirrors 70 are shifted along the optical path to assure that exit beam 69 arrives at focal point 60 at the same time as an electron bunch reaches the same point in undulator 22. Focal point 60 may be at any location in undulator 22 desired. This stimulates greater light emission, which in turn leads to a higher intensity pickoff beam 40 for the next cycle. The present invention is designed to prevent any runaway effect.

Ideally, a pulse expander-folding mirror would be a single parallel plate about 1-2 millimeters thick as shown in Fig. 3A. In Fig. 3 several mirror variations for use as expander mirror 44 are shown. In Fig. 3A, expander mirror 44 is a half-silvered mirror 45. It is half-silvered so that half of the incident beam 40 is reflected from the first surface 73 and the rest of it from the second surface 74. This is a possible configuration for a pulse expander-folding mirror. However beam 40 is very intense, and it is difficult to cool a glass plate. For a 200 kilowatt laser it will be possible to use, but as the laser output power increases, possibly to a megawatt, it becomes more difficult to cool. Fortunately there are alternatives which are

nearly as good as a refractive glass plate. They are mesa-like
structures with reflecting surfaces top and bottom, as shown in Fig. 3B
and Fig. 3C. The vertical separation between the parallel reflecting
surfaces is about 5 millimeters. Since they are mirrors, they can be
cooled efficiently by known techniques. The light beams reflected from
the top and bottom of the mesa are laterally displaced, but if the
beams are focused, they become superimposed and the resulting pulse-
length is twice what the incoming pulse length of the electron beam is.
The mirror structure is mounted at the entrance pupil of the focusing
optics 48, and it focuses the return beam near the entrance of
undulator 22, where the electron pulse train and the regenerative
optical pulse are combined as discussed above. At that point the
doubled pulse width from the reflective optics is optically equivalent
to that from the half-silvered mirror. Nearby the overlap is nearly as
good, and phase-matched stimulated emission will occur.

The simplest all-mirror configuration is shown in Figs. 3B and 5A.
The mesa direction may be lined up parallel to the beam direction or
rotated 90 degrees as shown. The mesa height L would be about 5 mm. A
better system with multiple mesas lying parallel to the beam direction
is shown in Fig. 3C and Fig. 6. Since the mesas are closer to each
other the effective overlap of the top and bottom of the mesa would
extend farther from the focal point of the Cassegrain system than in
the case of a single mesa. By orienting the mesas parallel to the beam
rather than perpendicular to it vignetting of the beam by the edge of
the mesa is eliminated.

Fig. 5A shows a mirror 46 used as the expander mirror 44 with one mesa of depth L. Beam 40 is now shown as a single pulse 79 of pulse length t traveling along optical path 80. Part of pulse 79 reflects off of raised mesa 64 as pulse 84 travels along optical path 81. The rest of pulse 79 reflects off of unraised portion 62 of mirror 46 as pulse 85 travels along optical path 83. By design the portion of pulse 79 reflected from unraised portion 62 is delayed one pulse length t so pulse 79 exits mirror 46 with a double pulse length. With mirror 46 oriented as shown, vignetting occurs due to the gap 82 between optical paths 81 and 83.

The height of mesa 64 may be of any thickness. For Fig. 5A, the thickness L is set at a height so that the leading edge of pulse 85 is timed to match the trailing edge of pulse 84. If step 64 is greater, there will be a time gap after pulse 84 passes before pulse 85 arrives. If step 64 is less, pulses 84 and 85 will partially overlap in time despite being physically offset. Each pulse has a duration time t. For the two pulses to match so the leading edge of pulse 85 matches the trailing edge of pulse 84 the step thickness can be calculated from the relation distance equals velocity times time.

If a phased step mirror 46 is used as in Fig. 5A, then pulse 84 and pulse 85 pass through aperture 56 shown in Fig. 2, each in a different portion of space as well as different time intervals. Pulses 84 and 85 are focused to focal point 58, which becomes the first place where the pulses combine spatially after being separated by mirror 46. By making the plane through focal point 58, the imaging plane for

refocusing optics 54, pulses 84 and 85 are brought to the same spatial point 60 solely separated by the time lag caused by phased mirror 46.

In Fig. 5B, half silvered mirror 45 has front surface 73 and back surface 74 as previously described. Optical pulse 90 of period t, again a parallel coherent light pulse, will have approximately 50 percent of pulse 90 reflected off of front surface 73 and the remainder reflected off of the rear surface 74. Light reflected off of front surface 73 will depart as optical pulse 92. Light reflected off of rear surface 74 will depart as optical pulse 94. Thickness T of half silvered mirror 45 will determine the time lag between the leading edges of pulse 92 and pulse 94. For purposes of example in Fig. 5B, thickness T produces a time lag sufficient to cause the trailing edge of pulse 92 to coincide with the leading edge of pulse 94. Adjusting thickness T can cause a gap between pulses 92 and 94 or cause them to partially overlap. While this is an alternate embodiment for an expander mirror, it is not the current preferred method because the light reflecting off of back surface 74 does cause internal heating which degrades the mirror performance.

If the one step mesa configuration shown in Figs. 3B and 5A is rotated 90 degrees so it is parallel to beam 40 then the side view would be similar to Fig. 3C except gap 82 is eliminated so vignetting is removed as a possible complication. However, by rotating to be parallel to the beam, a further option is now possible, strips of mesas. Fig. 7 is a perspective of a strip mesa expander mirror 61 suitable for use as expander mirror 44. Fig. 3C is a side view of striped mesa expander mirror 61. Striped mesa expander mirror 61 has

reflecting surfaces 62 alternated with raised reflecting surfaces 64.
Because all reflecting surfaces 62 and 64 form a single mirror, mirror
61 may be easily cooled by known techniques.

Fig. 6 is an oblique view showing the back and side of mirror 61,
in contrast to the side views of Fig. 3 and Fig. 5. Beam 40 is coming
from below in Fig. 6. Mirror 61 is angled as shown in Fig. 3C. Beam
40 has pulse t which now is reflected in the delayed pattern shown.
Because no gap spatially arise between these optical paths vignetting
is avoided. Because there is a layering effect of the expanded pulse
components and refocusing problems are reduced because smaller spatial
recombination problems are present between adjoining delayed pulse
components. Many more varieties for an expander mirror are clearly
possible.

Whichever of these options or others is shown for expander mirror
44, mirror 44 is at the focus of focusing optics and serves at a pupil
56. As shown in Fig. 2, focusing optics 48 may be a Cassegrain mirror
system. Refocusing optics 54 is also shown as a Cassegrain mirror
system. Since mirror 44 is at the focal point of focusing optics 48,
refocusing optics 54 will focus this pupil to undulator 22 where the
igniter laser pulse and the regenerative pulse are combined. Since
focusing optics 48 focuses the pickoff portion of convex mirror 42 onto
focal point 58, the beam then expands to fill refocusing optics 54. A
spatial filter, not shown, may be placed before focus 58 if desired.
Since focus 58 is at the focal point of refocusing optics 54, parallel
light beam 69 is emitted by refocusing optics 54, shaped and is sent to
pass through undulator 22. Since light from any point on a pupil, here

expander mirror 44, passes through every point on any image formed by
the optical system, here the parallel beam through undulator 22,
lateral phase nonuniformities in the expander mirror 44 caused by the
top or bottom reflectors are smoothed out and the stretched pulse from
the regenerative loop is laterally uniform.

A major advantage of the stepped mirror configuration is that the
possibility of damage to the pickoff system and distortion of the
wavefront of the reflected beam is greatly reduced. The laser output
of IFRA FEL has an initial power of 200 kilowatts and an ultimate power
of a megawatt or more. The diameter of the output beam is
approximately one centimeter. It then begins to expand. Approximately
2 percent of the output beam is deflected back into the feedback system
by mirror 42. Fully reflective mirrors can be cooled and if properly
designed have been shown experimentally to be able to handle over 2
kilowatts per square millimeter of power without mirror distortion.
(See R. M. Wood Laser Damage in Optical Materials (Adam Hilger,
Bristol, 1986), pp. 113 and 121.)

An additional advantage of the stepped mirror configuration is the
absence of transmission through an optical component. Not only does
transmission make it difficult to adequately cool the component but
defects in the material can cause hot spots which may not only scatter
light and deform the transmitted wavefront but may also weaken the
material and become a site for catastrophic damage. The thickness of
materials used in any mirror may cause scatter as the beam is both
reflected and partially transmitted from the front surface of the

material and the transmitted portion is then reflected from the back surface of the mirror.

If a phased mirror is used, the amount of separation L is set at a distance needed to produce adjoining pulses of a desired time lag. As an example, if a 24 picosecond pulse is desired, focus the existing beam at the optimum position within undulator 22. Separation L is then about 5 millimeter. The previously described adjustment means, not shown can move the pair of mirrors 70 to adjust the phase of the pulse.

If a half silvered pickoff mirror 45 is used as the pickoff means, the thickness T, as shown in Fig. 5B, will determine the amount of delay the transmitted light through top surface 73 will have after reflecting off of bottom surface 74. Front surface 73 is coated with a semitransparent material that reflects 50 percent or so of the light. The remaining light transmits to back surface 74, which is coated with a fully reflective coating. For incident light at 45° as shown in Fig. 5B, the light is refracted for a given index of refraction. The light then travels a distance in mirror 45, reflects off of the back surface and travels the same distance in mirror 45 before exiting. These paths are shown in dashed lines in Fig. 5B. Light reflecting off of the upper surface at the same location as the exit point for light from the back surface has traveled a different distance. Using the geometric relations shown in Fig. 5B with 34 picosecond pulses and a mirror 45 with an index of refraction of 1.5 1.5 yields a thickness 1.28 millimeters for T. For a stepped mirror as shown in Fig. 5A, the height L of the mesa for similar conditions is 5.09 millimeters. Such half silvered expander mirrors are commercially available.

Fig. 4 is an alternate embodiment of the present invention. Half silvered mirror 45 is shown as the expander means. Mirror 45 is used to redirect the pickoff beam 40 into focusing optics 48. Refocusing optics 54, which may also be a Cassegrainian arrangement, now produce an exit beam 69. The choice of whether exit beam 69 is a parallel or converging beam is the designer's choice and is not effected by the manner in which the expander beam is created. A plurality of mirrors, here shown as two concave mirrors 71 and 72, bring exit beam 69 to a focus at point 60 as shown before. These mirrors become part of refocusing optics 54 needed to refocus the imagining plane to point 60. There are many other arrangements to refocus the imaging plane through focus point 58 to point 60 in undulator 22. Also, in Fig. 4, mirrors 70, 71, and 72 may be mounted on an optical table not shown which is adjustable in three dimensions along the optical path for the same reasons as discussed above. The adjustment of concave mirror 71 is illustrated by double headed arrows. The other mirrors can be similarly adjusted in three dimensions, if desired.